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ANNUAL REPORT

HIGH PRESSURE TRANSDUCER

15 June 1973

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RECONNAISSANCE ELECTRONIC WARFARE
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GTE SYLVANIA
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ELECTRONIC SYSTEMS GROUP/WESTERN DIVISION

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Annual Report

HIGH PRESSURE TRANSDUCER

by

Dr. G. Kirby Miller

15 June 1973

Contract Number N00014-72-C-0307

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Prepared for:

Scientific Officer
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ABSTRACT

A promising new line mechanoelectrical transducer based on the electret phenomenon is considered for use as a variational pressure sensor in the underwater environment. Theoretical design considerations are developed for these coaxial cable devices with regard to sensitivity, geometry, frequency, input electronics type, and ambient pressure. Test results are reported comparing samples of one type of cable transducer to a calibrated hydrophone under two different test setups, for a variety of ambient pressures, and using two different types of excitation. In these tests, the cable transducer is found to compare favorably with the standard hydrophone with respect to sensitivity and independence of ambient pressure up to 2500 psi.

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Annual Report

HIGH PRESSURE TRANSDUCER

1.0 INTRODUCTION

This report describes the work done by the Security Systems Department of GTE Sylvania's Mountain View, California facility during June 1972 to June 1973 under contract to the Office of Naval Research.

1.1 BACKGROUND

In the past few years the Security Systems Department has become deeply involved in the development of long, linear transducers capable of detecting mechanical excitation at any point along their lengths. These are very useful in intrusion detection systems, especially for protecting perimeters. The most recent versions are coaxial cables processed in such a way that the dielectric layers between the conductors retain a charge polarization for many decades. Such a dielectric is called an electret, and these transducers are often referred to as electret cables. They are sensitive to any change in spacing between one of the conductors and the charge distribution in the electret at any point along their length.

Although not specifically designed for underwater applications, the electret cables do respond to underwater acoustic signals. This was established by direct experiment at atmospheric pressure. Recognizing the potential for such transducers in naval applications, ONR supported the program reported here.

1.2 PROGRAM OBJECTIVES

The following are the main objectives established for the program:

1. Establish underwater acoustic sensitivities for electret cable transducers (and possibly other electret transducers) in the frequency range 10-1000 Hz, and compare with theoretical values.

2. Determine the effect of pressure (if any) on the transducers in the range from 1 to 170 atmospheres for the same frequency range.

1.2 (Continued)

3. Develop an understanding of the causes of performance variations under different environmental conditions to allow recommendations for the design of improved transducers.

1.3 PROGRAM ORGANIZATION

Given the above objectives the program is organized into the following steps.

First, a theoretical examination of the cable's behavior, both electrically and mechanically, when subjected to the underwater environment at various pressures is undertaken. This includes consideration of the changes in mechanical properties of the cable materials at various stress levels. It also includes the effects of the given frequency range of interest on the monitoring electronics and on the permissible properties of the transducers. Designs other than the available coaxial cable configuration are also considered.

Barring negative results in the theoretical examination, a small-scale in-house experimental program for testing a few cable transducer samples underwater at pressures up to that supplied in the lab compressed air line is undertaken. This test should determine the feasibility of using the cables as hydrophones and should serve to identify any construction problems likely to be encountered (such as watertight seals).

After any bugs discovered from the previous work are eliminated, a larger-scale set of tests are carried out at the Lockheed high-pressure testing facility. Here the effects of high pressure on the transducer performance are determined.

Finally, the data are analyzed and consolidated to arrive at an evaluation of the tested transducer's performance.

2.0 TRANSDUCER DESIGN CONSIDERATIONS

It is hoped that an electret transducer can be developed which will retain good sensitivity to underwater acoustic signals in the frequency range of 10-1000 Hz while operating at ambient pressures of 1 to 170 atmospheres. The coaxial cable configuration has received the most attention prior to this study for above-water applications, and was considered to be an important candidate for the present purpose.

2.1 COAXIAL CABLE TRANSDUCER

The configuration to be discussed here is shown in the diagram of Figure 2-1. Depending on the dimensions and materials this sketch could represent any of a large number of commercially available cables.

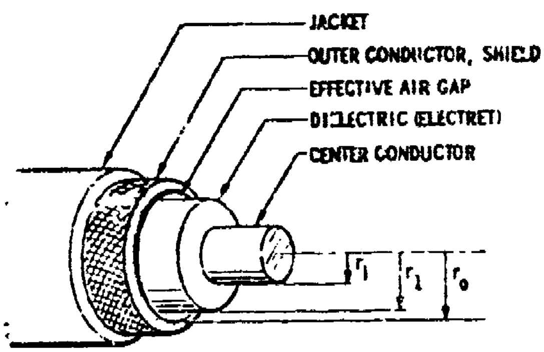


Figure 2-1. Coaxial Cable Transducer

Since various flourocarbon materials seem to make the best electrets, we consider only dielectric layers made of these materials. The conductors may be of copper or coated copper wires, usually stranded for the center conductor and braided for the shield layer. The jacket layer is usually of the same material as the dielectric. This is not necessary for the operation of the transducer, but is convenient since the electret charging treatment involves heating up the cable to at least 180°C. Most non-flourocarbon materials would melt or be destroyed under these conditions. After

2.1 (Continued)

the cable is charged, one end is sealed by potting (after the center conductor tip is shielded) and the other is sealed to a waterproof connector.

Mechanical motion of the shield relative to the electret layer causes charges to flow in the conductors which can be sensed by either a voltage or current amplifier.

2.1.1 Voltage Analysis

The voltage measured across the effective shunt resistance, R, between the two conductors when the entire transducer is subjected to an external small variational pressure, p, is given by

$$v = A\,p\,E\,k\,r_i \left\{ K \left[1 + k\,\ln\left(1 + \frac{a}{r_i + d}\right) \Big/ \ln\left(1 + \frac{d}{r_i}\right) \right] \sqrt{d\left|1 + (\omega RC)^{-2}\right|} \right\}^{-1} \qquad 2\text{-}1$$

where

A	is a constant
E	is the breakdown electric field in the electret
K	is the radial stiffness of the shield and sheath
k	is the relative permittivity of the dielectric (electret)
r_i	is the radius of the center conductor
d	is the thickness of the dielectric layer
a	is the thickness of the effective air gap between dielectric and shield
ω	is the radian frequency of p
R	is the input resistance of the electronics attached to the cable
C	is the capacitance of the cable.

This expression is valid for the case in which the cable is charged with an applied DC voltage producing a field intensity which is a given fraction of the break-down field intensity of the electret. See Technical Report I for the derivation.

From Equation 2-1 it may be inferred that for greatest cable sensitivity, the dielectric strength, dielectric constant, and center conductor diameter should be

2.1.1 (Continued)

maximized while the radial stiffness of the shield (and sheath) and the air gap width should be minimized. The dielectric thickness should also be made small, but should remain at least several times greater than the air gap. The radical containing the frequency dependence represents a low-frequency roll-off characteristic for values of $\omega R C < 1$. In order to avoid this loss the product $f R_M \ell$ should be kept in the range

$$f R_M \ell \geq \frac{9000}{\pi} \left[\ln\left(1 + \frac{a}{r_i + d}\right) + \frac{1}{k} \ln\left(1 + \frac{d}{r_i}\right) \right] \qquad 2\text{-}2$$

where

f = frequency (Hz)

R_M = resistance of electronics (MΩ)

ℓ = length of cable (meters)

Figures 2-2 and 2-3 illustrate the above equations showing the effects of cable geometry on its voltage sensitivity. To eliminate frequency effects, Figure 2-2 is plotted at the critical value of $f R_M \ell$ (the equality condition in Equation 2-2). These critical products are plotted as functions of cable geometry in Figure 2-3. For each factor of two by which the critical value of $f R_M \ell$ exceeds the actual $f R_M \ell$ product, the output voltage of the cable drops ~ 6 dB below the value shown in Figure 2-2.

For example, consider a coaxial cable with a 10 ga center conductor and a 20 mil dielectric thickness. The cable output is between 25 and 28.5 dB on the relative scale of Figure 2-2 depending on what the effective air gap is (closer to .2 or to 5 mils ?). The critical product is (from Figure 2-3) between 430 and 725. Thus, for a transducer of length 0.5 m and a signal at 10 Hz, the input impedance, R_M, should be at least 145 MΩ to avoid the roll-off loss. This value could be lowered without reducing sensitivity by using longer cables, or cables with greater capacitance per unit length, or by working at higher frequencies.

Figure 2-2. Cable Output at Critical Product $(fR_m \ell)_{crit}$ as a Function of Cable Geometry for Hydrostatically Applied External Pressure

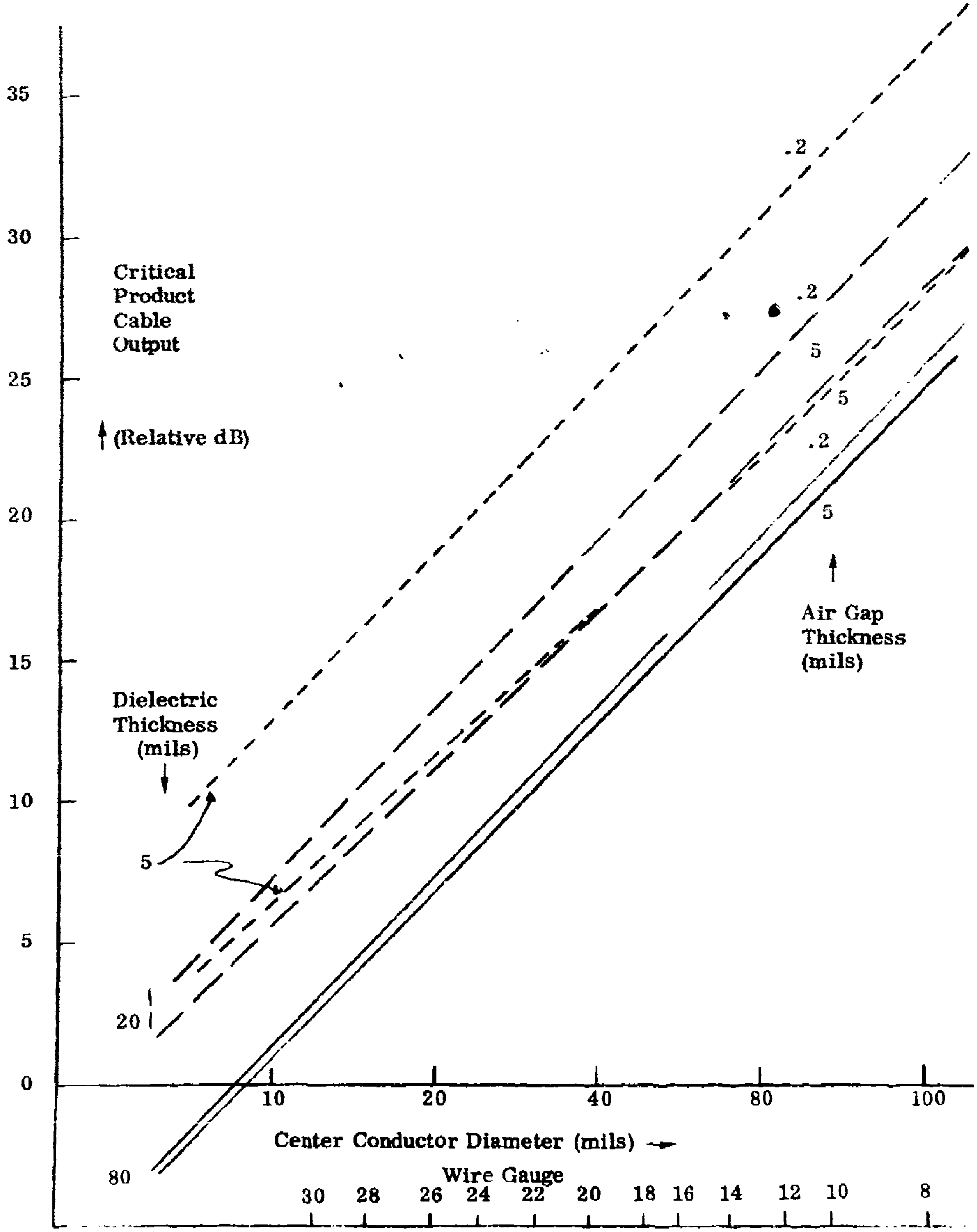
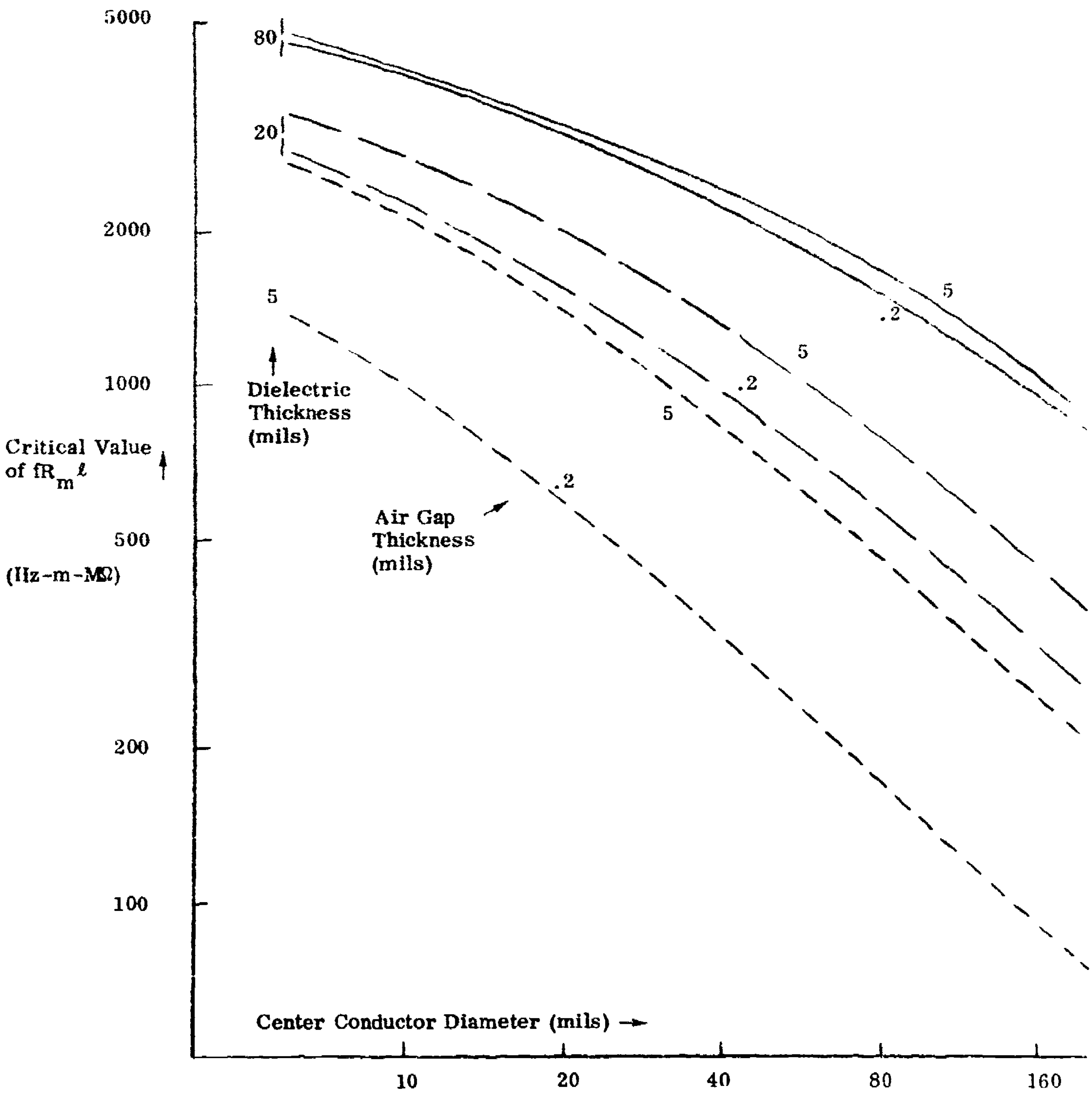


Figure 2-3. Cable Cutoff Product as a Function of Cable Geometry



2.1.2 Charge Analysis

There are often problems with noise when using a very high input impedance voltage amplifier on signals of very small amplitude. In addition when only part of the cable is excited mechanically the voltage output is inversely proportional to the total length of the cable. However, since the mechanical disturbance being measured is independent of the length of the cable, it is usually desirable for the output of the transducer to also be independent of length. For these reasons it was considered worthwhile to examine the charge rather than voltage sensitivity of the cable, and also to see what advantages might be gained by electronically sensing the charge flow rather than input voltage.

A general expression for the variational charge, q, due to a variational pressure, p, which would flow between the electret-separated conductors through a short-circuit at one end of a line electret transducer is given by

$$q = \frac{p\,\ell\,C^2\,v_e}{4\,\pi\,\epsilon_o\,K} \qquad \text{2-3}$$

where

ℓ	=	transducer length exposed to p
C	=	transducer capacitance per meter
v_e	=	frozen polarization voltage of electret
ϵ_o	=	permittivity of free space (or air)
K	=	effective radial stiffness of moving (outer) layer(s)

This expression is derived in Appendix B of Technical Report I. Usually the strength of the electret is given in terms of the effective surface charge density, σ. In the coaxial cable case this is related to the electret voltage, v_e, by

$$v_e = \frac{\sigma}{\epsilon}\,(r_i + d)\,\ell n\,(1 + \frac{d}{r_i}) \qquad \text{2-4}$$

The radial stiffness of a hollow tube of material with an elastic modulus (Young's modulus) Y, is well approximated at frequencies well below radial resonance by

$$K = .25\,Y\,[\,1 - (1 + t/r_o)^{-2}\,] \qquad \text{2-5}$$

2.1.2 (Continued)

where

r_o is the inner tube radius

t is the wall thickness of the tube

See Equations 2-6 to 2-10 for a derivation of 2-5. In our case this expression can be used to estimate the radial stiffness of the shield jacket layers. Figure 2-4 shows a set of design curves based on Equations 2-3, 2-4, and 2-5 in which $\sigma = 10^{-4}$ C/m^2 for the surface charge density, $Y \approx 4.5 \times 10^8$ N/m^2 for teflon, and $t = 13$ mils for a typical effective wall thickness.

As in the voltage analysis these curves indicate greater cable output for larger center conductors. However, in this case for the smaller center conductors it is advantageous to have larger dielectric thicknesses rather than small ones. It must be remembered that the perspective is somewhat different in this figure than in the previous two. Here the electret's charge density is assumed fixed regardless of cable dimensions, whereas before the charge density was assumed to depend directly on the breakdown field strength of the dielectric (which was assumed to vary inversely with the square root of the dielectric thickness).

Figure 2-5 illustrates the effect of cable geometry on charge flow exactly as in Figure 2-4 except that the electret is again assumed to be treated with a field intensity which is a constant fraction of the breakdown intensity and the breakdown intensity varies inversely with the square root of the thickness of the dielectric. This is probably a more realistic set of curves for design purposes.

2.2 PRESSURE EFFECTS

The transducer sensitivity expressions of the previous section depend on both the radial stiffness of the moving layers as well as on the dimensions of all layers. Large changes in pressure are expected to effect both stiffness and the dimensions. In this section some effects of pressure are considered theoretically.

Figure 2-4. Effects of Dimensions on Charge Output of Coaxial Electret Cable Exposed to Pressure (Surface Charge Density Fixed)

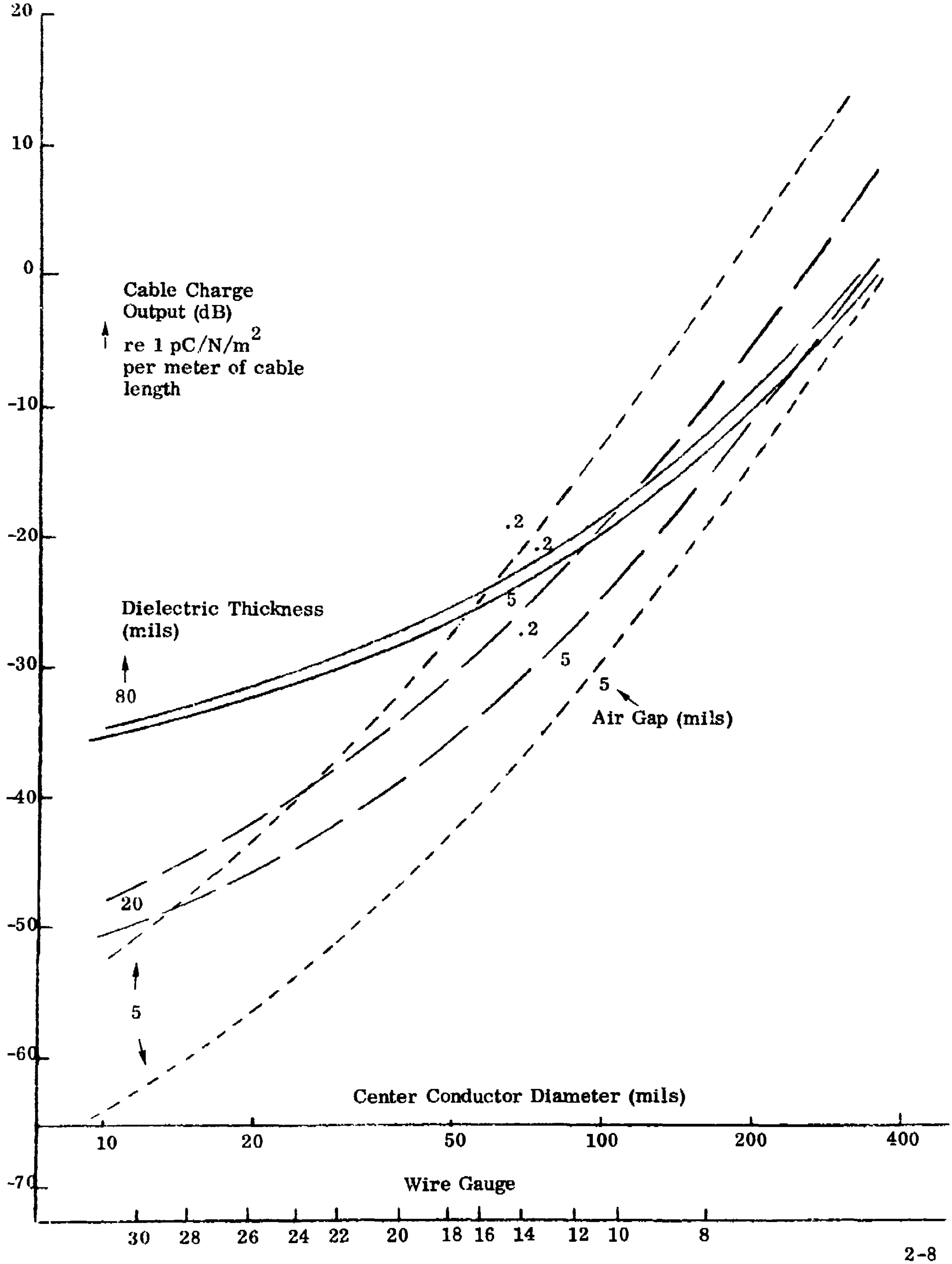
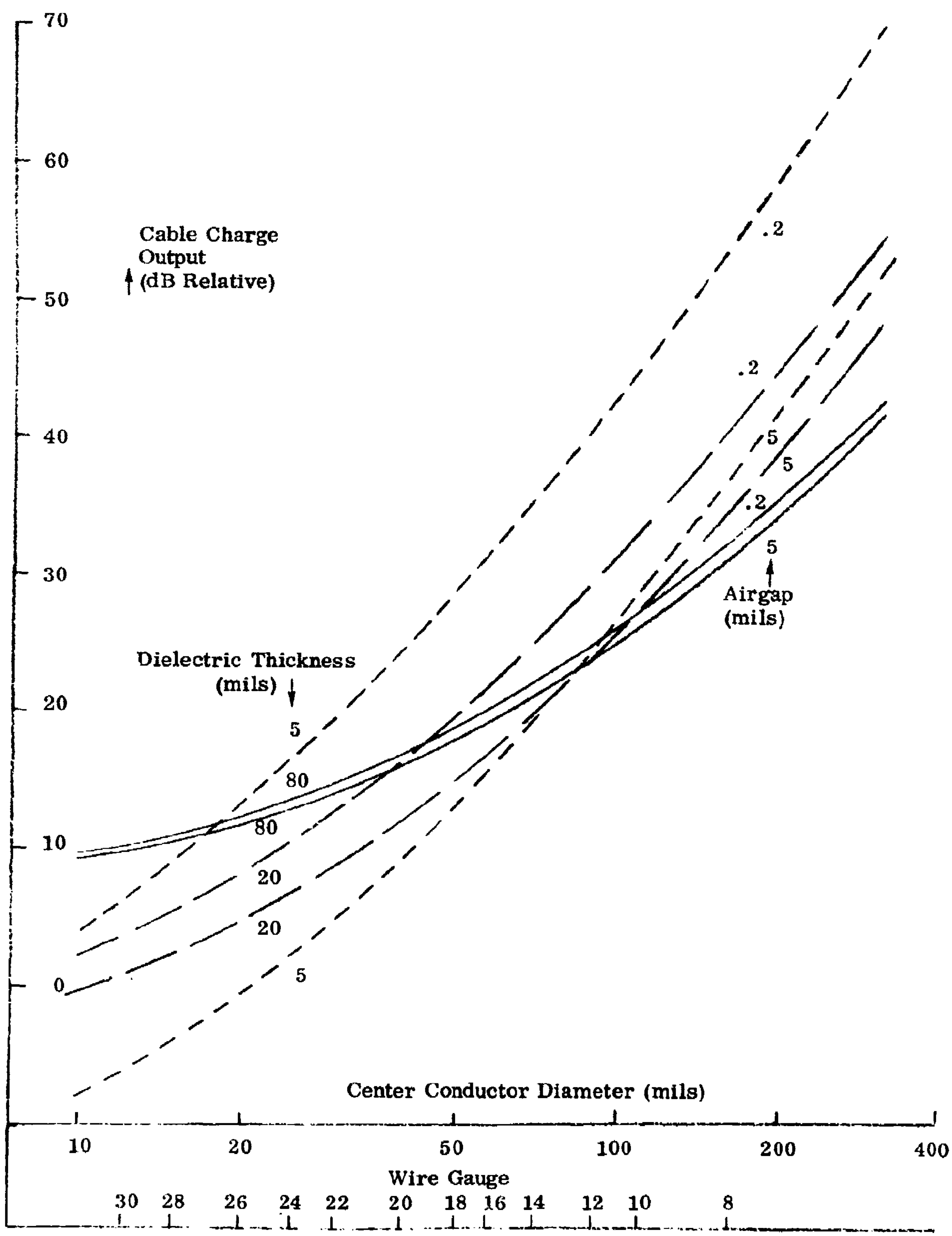


Figure 2-5. Effects of Dimensions on Charge Output of Coaxial Electret Cable Exposed to Pressure



2.2 (Continued)

The effect of internal pressure, P_i, and external pressure, P_o, on the dimensions of a long hollow elastic cylinder initially of inner and outer radii a and b respectively is given by Timoshenko and Goodier in Theory of Elasticity, third edition, page 70 (in a slightly different form) as

$$\frac{\Delta r}{r} = \frac{1}{Y(b^2 - a^2)} \left[-(1+\nu)\frac{a^2 b^2}{r^2} (P_o - P_i) + (1-\nu)(P_i a^2 - P_o b^2) \right] \qquad 2\text{-}6$$

for $a \leq r \leq b$

This expression for radial strain is sufficiently general to be applicable to the study of strain in three cases: free-flooding hollow cylinder, solid cylinder, and hollow cylinder with external pressure only.

For the free-flooding cylinder $P_o = P_i$, so

$$\frac{\Delta r}{r} = -P_o \left(\frac{1-\nu}{Y}\right) \quad a \leq r \leq b \qquad 2\text{-}7$$

Curiously the identical result is obtained for the solid cylinder ($a = 0$) exposed to the static pressure, P_o. Equation 2-7 shows that for a given static pressure increase the fractional change in radius for a point in a solid or free-flooding hollow cylinder is a constant depending only on the Poisson's ration, ν, and Youngs modulus, Y, of the elastic material from which the cylinder is constructed. The negative sign indicates that external pressure causes inward radial particle displacements.

Unfortunately for some materials of interest, the elastic modulus is a strong function of the static pressure, P. Equation 2-7 should not be used without awareness of that fact.

The third case is for a hollow cylinder in which the external pressure $P_o = P_i + \Delta P$. Then Equation 2-6 can be cast in the form for $r = a$ of

$$\frac{\Delta a}{a} = \frac{-2\,\Delta P\, b^2}{Y(b^2 - a^2)} - \frac{P_i}{Y}(1-\nu) \qquad 2\text{-}8$$

Note that if P_i = atmospheric pressure the second term is simply the radial strain caused by exposing the tube to atmospheric pressure. If we are interested in the

2.2 (Continued)

strain caused by the excess pressure, ΔP, this is given by the first term. Since the radial stiffness is defined by

$$K = \frac{r \, \Delta P}{2 \, \Delta r} , \qquad \text{2-9}$$

the radial stiffness at r = a can be estimated using 2-9 and the first term of 2-8 as

$$K = -.25 \; Y \left(1 - a^2/b^2\right) \qquad \text{2-10}$$

The strain at r = b due to excess pressure ΔP is

$$\frac{\Delta b}{b} = - \frac{\Delta P}{Y} \left(\nu + \frac{b^2 + a^2}{b^2 - a^2} \right) \qquad \text{2-11}$$

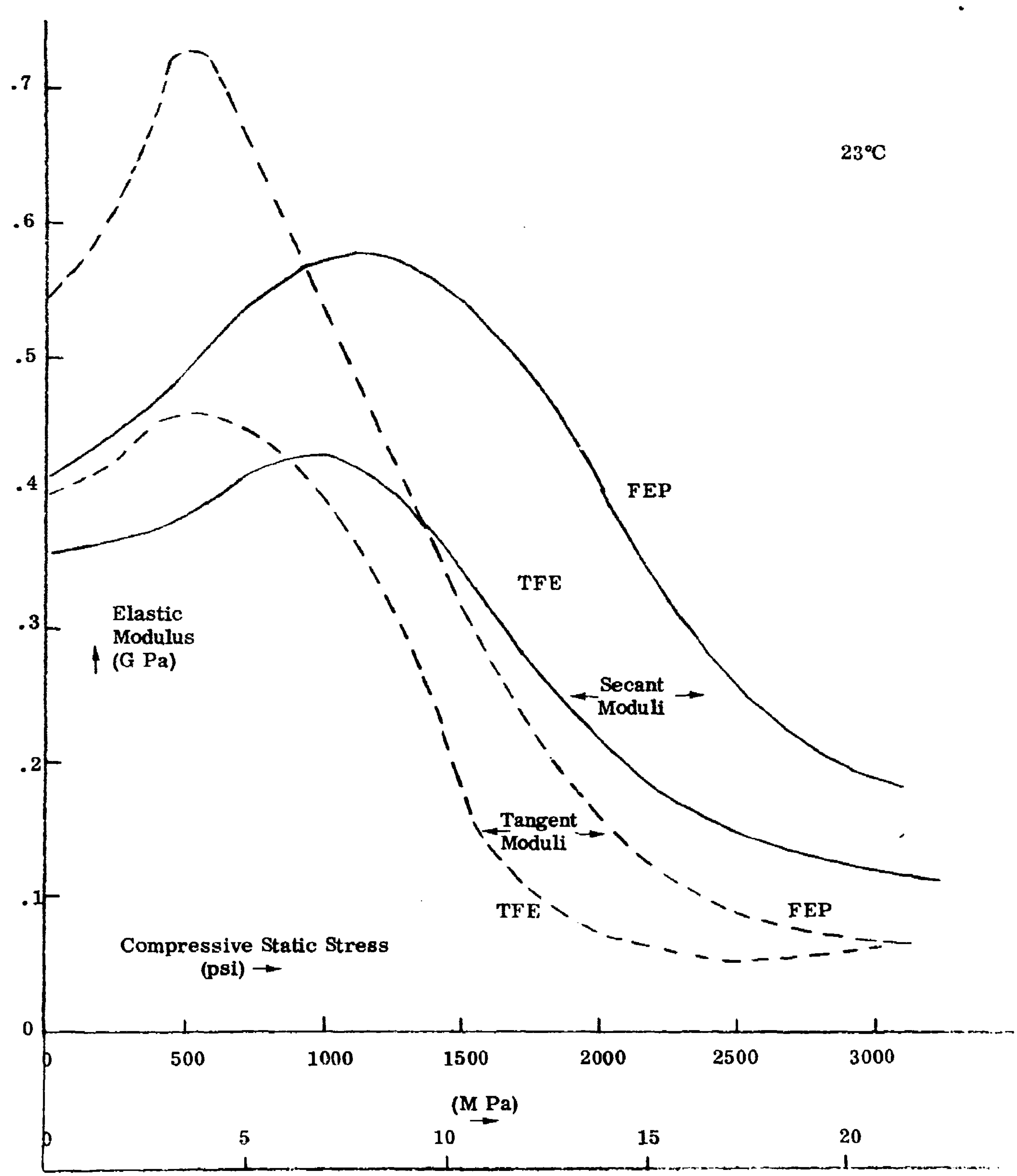
It should be mentioned that, being derived from the solutions to the linearized differential equations of elasticity, the foregoing expressions are only strictly valid for very small deformations. However, they also serve as upper bounds for estimating the deformations caused by the very large excess pressures of interest here.

Specifically, P_o = 2500 psi ≐ 170 atmospheres ≐ 17.2 M pa is the maximum ambient pressure of interest in this study. According to Dupont, for a compressive stress of 17.2 M Pa the total unconstrained strain is about 6.5% for FEP and 11.6% for TFE both at 23°C. Figure 2-6 illustrates the variation of the unconstrained elastic modulus with compressive stress for teflon.

As the ambient pressure is raised the difference in pressure between the air gap and the jacket surface causes the jacket to be compressed. The deformation continues radially inward until the combined stiffness of the compressed air in the air gap and the shield-jacket layer provide restoring forces which achieve equilibrium with the external pressure.

As an example of this process consider an FEP coax cable with center conductor diameter 55 mils, 10 mil thick dielectric and jacket layers, an 8 mil thick braided shield, and an effective air gap of 3 mils between the shield and the dielectric. This is the cable most used in later experiments. Using Y = .48 G Pa and ν = .48 for

Figure 2-6. Effect of Pressure on Unconstrained Elastic Modules for Teflon



2.2 (Continued)

FEP teflon and assuming an effective thickness for shield and jacket of 13 mils of teflon, we find that an external pressure of 10 atmospheres causes a radial strain of about 4.6% at the inner radius of the shield. For an original shield inner radius of 68 mils this would represent a decrease of about 3.1 mils. This means that the pressure in the original air gap of 3 mils is greatly increased and that the electret layer is also compressed.

The air in the air gap is a very linear material even up to over 100 atmospheres. that is, its pressure-volume product remains a constant within a percent or so. Thus, to compress the air to 1% of its original volume requires 100 atmospheres. Table 2-1 gives the air gaps corresponding to various pressures when the inner radius is maintained constant at 65 mils.

Table 2-1

Pressure (Atmospheres)	1	5	10	20	100	170
Remaining Air Gap (mils)	3	0.65	0.36	0.21	0.10	0.08

This table shows that as pressure increases, the air gap quickly gets very small, but remains an appreciable fraction of a mil even up to 170 atmospheres. The actual air gap would be somewhat greater than shown in Table 2-1 because of the fact that the inner surface of the air gap would be compressed. Note that the effective air gap remains considerably larger than the expected signal-caused displacements. Also the air's bulk modulus, though increasing directly with pressure, remains much smaller than than of teflon. Thus, at high pressures, the motion caused by a signal is expected to be determined more by the stiffness of the air than by the stiffness of the shield and jacket. Eventually, when the air is very stiff, the radial stiffness at the outer surface of the electret may also contribute appreciably to limit the motion caused by a signal pressure.

3.0 EXPERIMENTS

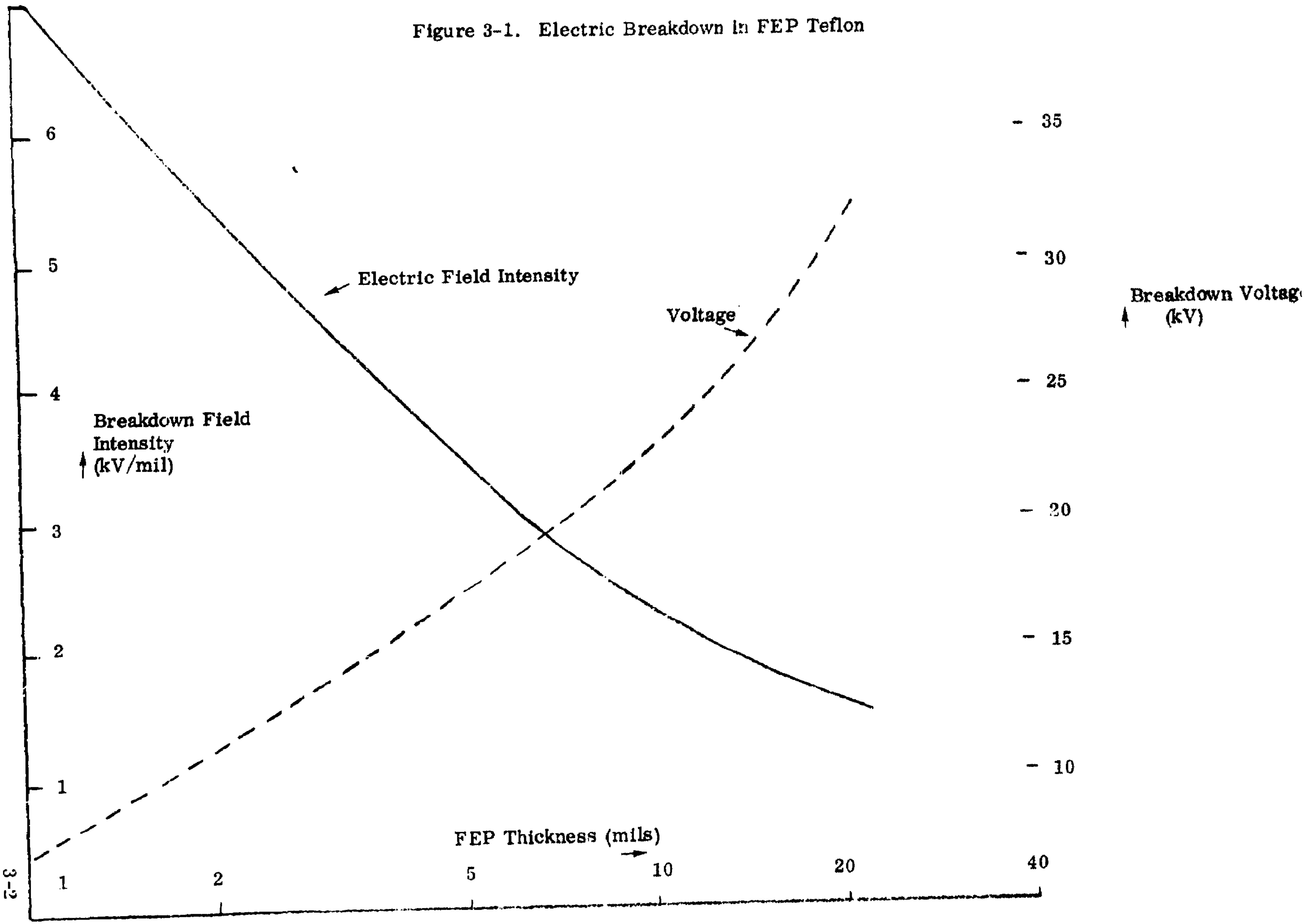
Although the theoretical work was encouraging, an experimental program was considered essential for testing the effects of pressure on the transducers. The plan was to obtain materials, fabricate and prepare the transducer candidates, test them in our lab on a small scale, and then test them in a high pressure facility maintained by Lockheed in Sunnyvale, California. Initially, a number of designs were considered; but due to the limited nature and the feasibility orientation of the program, it was decided to concentrate on a coaxial cable design which had proved successful in above-water applications.

3.1 THE TRANSDUCER

The transducer used for the experimental program is a coaxial cable with a 10 ga center conductor of silver-coated copper strands, a 10-mil thick FEP teflon dielectric layer, a 90% coverage woven shield of silver-coated copper strands (#36), and a 10-mil thick jacket of FEP teflon. The teflon layers are extruded. All transducers were cut to three feet in length and charged using high voltage. Figure 3-1 shows the electrical breakdown characteristics of FEP at room temperature. This indicates that dielectric breakdown for the test samples (10 mil thickness) is likely to occur before 23 kV at room temperature. When exposed to high temperatures the breakdown value decreases. We used voltages from 7.5 kV to 22.5 kV and temperatures from 20°C to 250°C for charging twenty-five cable samples in treatments lasting from four to eight hours. The basic procedure is to apply the voltage, heat the cable and sustain both for a measured period, after which the cable is cooled to room temperature while sustaining the voltage. In some cases samples were heat cycled once before the above treatment. In general, this seemed to improve the sensitivity of the sample cable following any additional charging treatment.

The ends of each cable were carefully potted to make the critical region between the shield and the dielectric waterproof. It was mainly to test the success of this potting that we made initial submergence tests in the lab.

Figure 3-1. Electric Breakdown in FEP Teflon



3.2 EARLY LAB TESTS

After preparing the first ten samples it was desired to test their performance in water to check for any obvious problems before going to the full-blown pressure facility. The plan was to put a transducer sample side-by-side with a calibrated hydrophone in a tank filled with water and compare the outputs of the hydrophone and cable transducer when the tank was excited mechanically. Figure 3-2 shows a sketch of the test setup. The Aquadyne AQ-13 hydrophone and AQ-125 preamplifier were purchased for these tests. This hydrophone is rated for 5000 psi and was calibrated at 100 and 1000 psi by Aquadyne at frequencies from 2 to 1000 Hz. Its sensitivity at both pressures is -97.3 dB re 1V/microbar from 10 Hz to 1000 Hz. The electronics used for the cable transducer is a charge amplifier with a frequency response down 3 dB at 10 and 1000 Hz and a maximum sensitivity of 0.96 V/pC.

The 3-1/2 foot pipe chamber was also fitted with an air valve so that it could be pressurized using the lab compressed air. To produce a signal the side of the pipe was tapped with a finger or well-damped object.

Figure 3-3 shows a photograph of simultaneous scope traces from sample #3 and the hydrophone after two days of soaking at 5 atmospheres of pressure. The pressure at the time of the photograph was still about 5 atmospheres. Note the main ringing at $\sim$ 500 Hz in both signals. This is the main mechanical resonance excited and is superimposed on a $\sim$15 Hz low frequency signal which probably represents the resonance of the chamber as a whole with its elastic pad support. The cable transducer seems to pick up this low frequency more than the hydrophone, while the latter appears to sense a small higher frequency component which is invisible to the former.

Although a study of these waveforms along with additional experiments could lead to a cleaner lab setup and experiment, the important point is made that even after two days of submersion at 5 atmospheres of pressure, the cable transducer retains a good sensitivity and responds similarly to a hydrophone. In fact, the sensitivity for the transducer derived from Figure 3-3 and using the hydrophone manufacturer's calibration data turns out to be .02 to .05 pC/μbar. This compares very well with the theoretical calculation of 0.06 pC/μbar per meter of cable based on Figure 2-4, which assumes an effective charge density of 10^{-4} C/m^2. The voltage produced by the cable transducer is typically a factor of 4 greater than that from the hydrophone for a given common excitation. These encouraging results supported the plan to prepare for testing at the Lockheed high pressure facility.

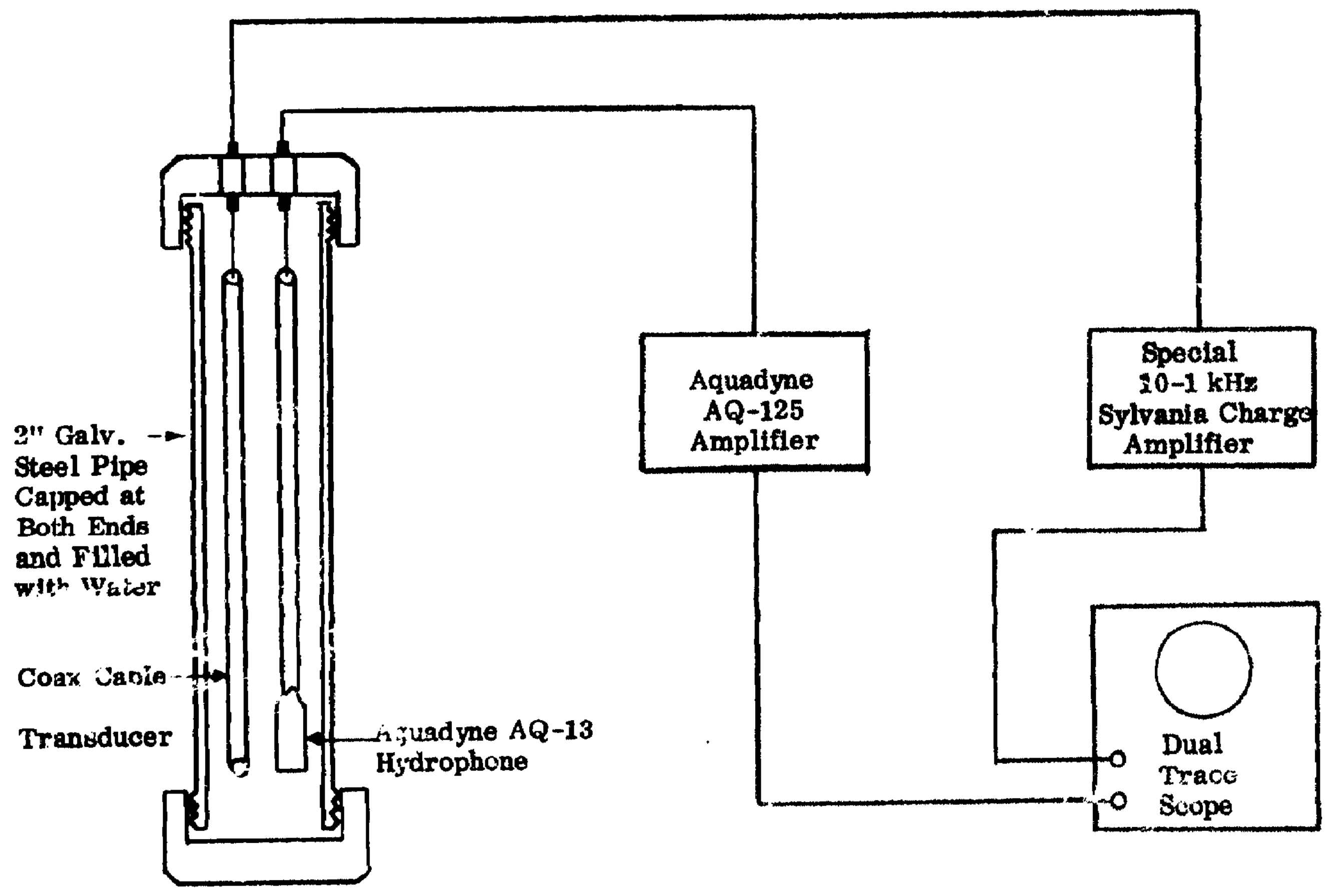
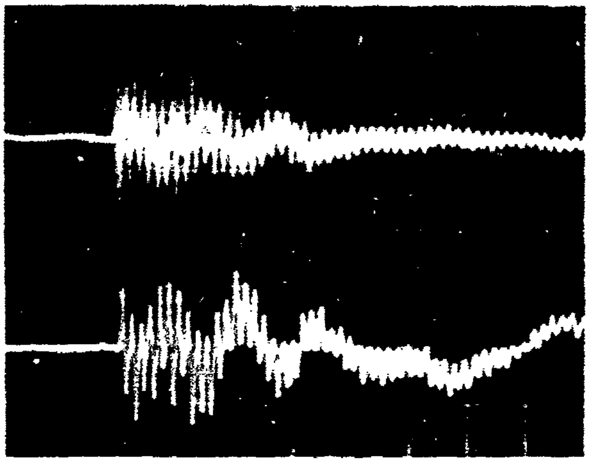


Figure 3-2. Instrumentation for Lab Submergence Test



Hydrophone

Cable Transducer

Figure 3-3. Comparison of Cable Transducer and Hydrophone

3.3 LOCKHEED TESTS

3.3.1 Equipment

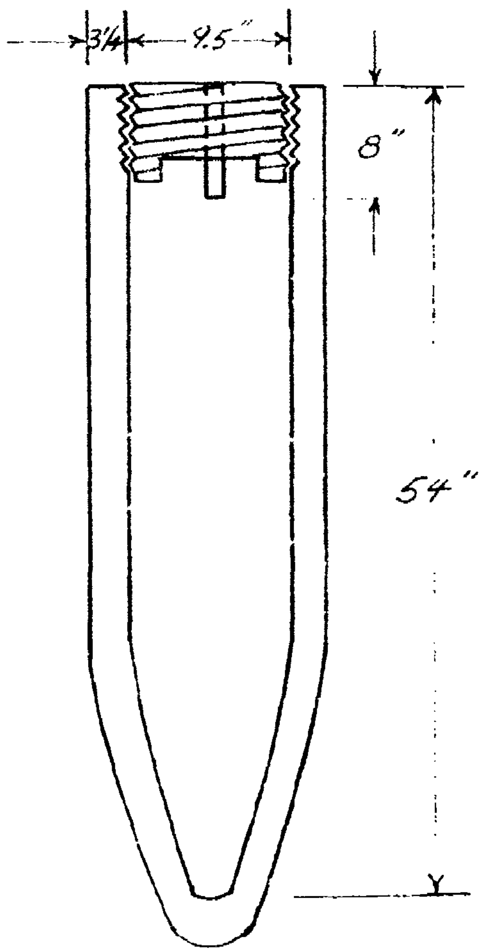
Figure 3-4 shows a scaled cross section of the pressure chamber maintained by Lockheed. This tank can be pressurized to 10,000 psi very rapidly and the pressure can be closely controlled and monitored. It is just long enough to comfortably contain our three foot samples without contact except at the suspending end. A complicated feed-through plate called the penetrator is fitted with feed-through terminals to which leads may be connected to provide communication from inside to outside of the chamber. We requested shielded leads be installed but this was not done because the feed-throughs were of the single pin type and inherently unshielded. To facilitate the changing of test samples it was decided to use silicone oil rather than water so that each sample need merely be fitted with the proper pin connector to mate with the feed-through pins. The facility was experienced in running with such silicone fluids and it was not a difficult change to make, but was expected to save considerable time in allowing quick sample substitutions. Using water the leads would have to be insulated from the fluid which would mean using very expensive waterproof, high-pressure connectors or alternatively potting each lead junction in the tank at installation time.

A diagram of the measurement setup is shown in Figure 3-5. Filters are used to restrict the frequency band to 10-1000 Hz and scope or chart recorder displays are available. FM tape recording is also available. The charge amplifier and hydrophone amplifier are those used in the lab tests.

3.3.2 The Experiment

After hanging the selected samples from the penetrator by rubber bands, the penetrator was secured and the air remaining in the tank pumped out. Then a rubber or plastic mallet was used to rap on the outside of the tank close to its base, and the hydrophone and cable transducer signals were observed on the scope or chart recorder. Because the upper frequency limit of the chart recorder is 125 Hz it was usually fed a DC signal out of an RMS voltmeter which represented the rms value of the signal in the pass band. However, most of the energy appeared to be below 125 Hz so that direct recording was also of interest.

After overcoming the usual hum and noise problems, results for sample #4 looked very much like our own lab results reported in the previous section (with the



Scale 1' = 1"

Figure 3-4. Lockheed High Pressure Test Chamber

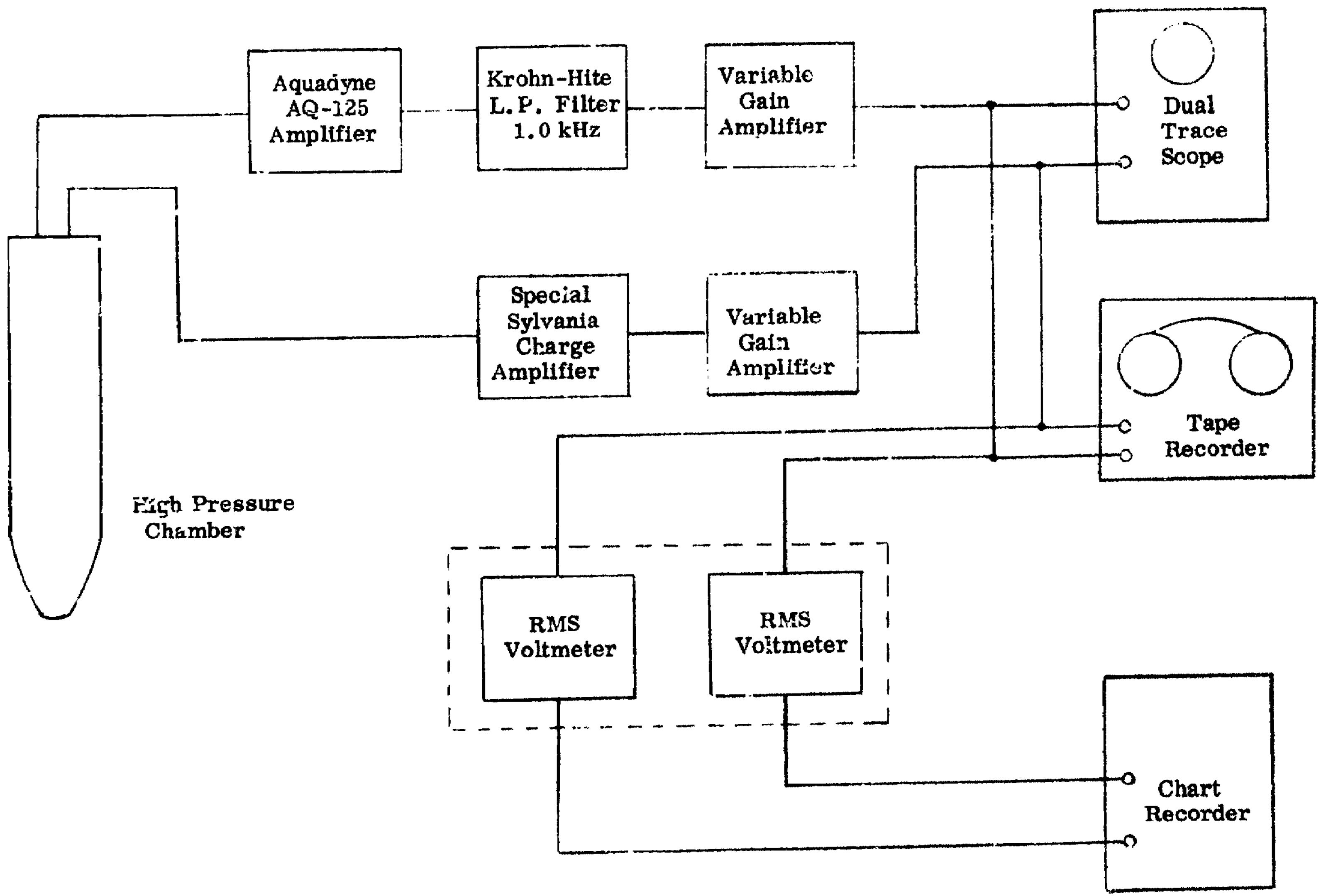


Figure 3-5. Instrumentation Block Diagram

3.3.2 (Continued)

cable putting out three to four times the voltage that the hydrophone produced for the same excitation). However, after leaving the samples soaking overnight it was found that they lost their sensitivity. Furthermore, a second set of samples lost their sensitivity after being pressurized to 2500 psi.

To ascertain the sensitivity loss, a laboratory bench test, which had been performed on the samples before the fluid tests, was repeated. In every case the measured sensitivity to the standard hammer drop (see Figure 3-6 for the set up) was found to be much lower after the sample had been submerged in the silicone fluid over night or had been submerged in it under 2500 psi pressure for a period on the order of an hour. The measured sensitivity loss in seven different samples varied from 14 to 32 dB with a typical loss of 20 dB. This result was disturbing enough to halt further tests until we could find the problem.

By carefully examining the samples with degraded sensitivity it was found that silicone oil had penetrated the potting and was in the woven shield layer of the transducer. Further talks with people who have had experience with silicone oils produced evidence that such oils are extremely difficult to seal against. In view of these findings and our successful laboratory experiment using water, we decided to change the fluid in the Lockheed tank to water.

Another 15 samples were prepared and tested for sensitivity using the laboratory setup shown in Figure 3-6. After a few more rounds of improving the S/N by improving the shielding, lowering the contact resistances, and improving the potting methods, some more encouraging results were obtained.

By recording the sound of the pump during previous pump-ups, we had determined that the pump signal was actually a better signal than we could introduce by rapping the exterior of the tank with a hammer. The pump signal is more repeatable and less likely to introduce the effects of vibration into the test. In addition, the pressure is easily monitored during pump up, so that relative sensitivity versus pressure data is rapidly obtained.

The pump signal consists of a large pulse followed by a smaller pulse each pump cycle. Each pulse is followed by decaying ringing at a frequency probably characteristic of the predominant acoustic mode which the chamber will support. Figure 3-7 shows a chart recording of a single pump cycle as recorded by cable sample 18 and the hydrophone (out of phase) at 250 psi and at 1500 psi. Note that the ring frequency

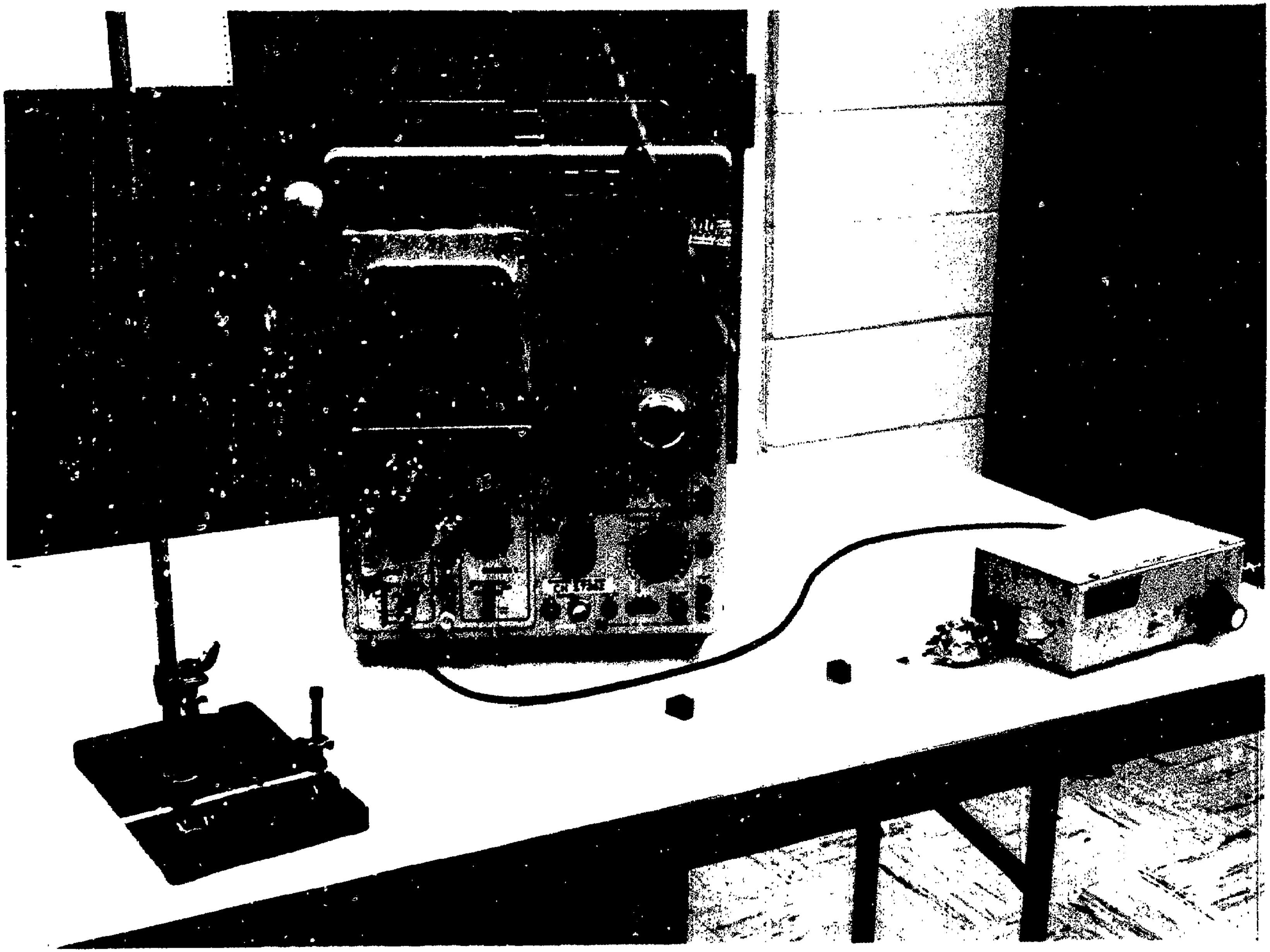


Figure 3-6. Lab Set-Up for Sensitivity Test

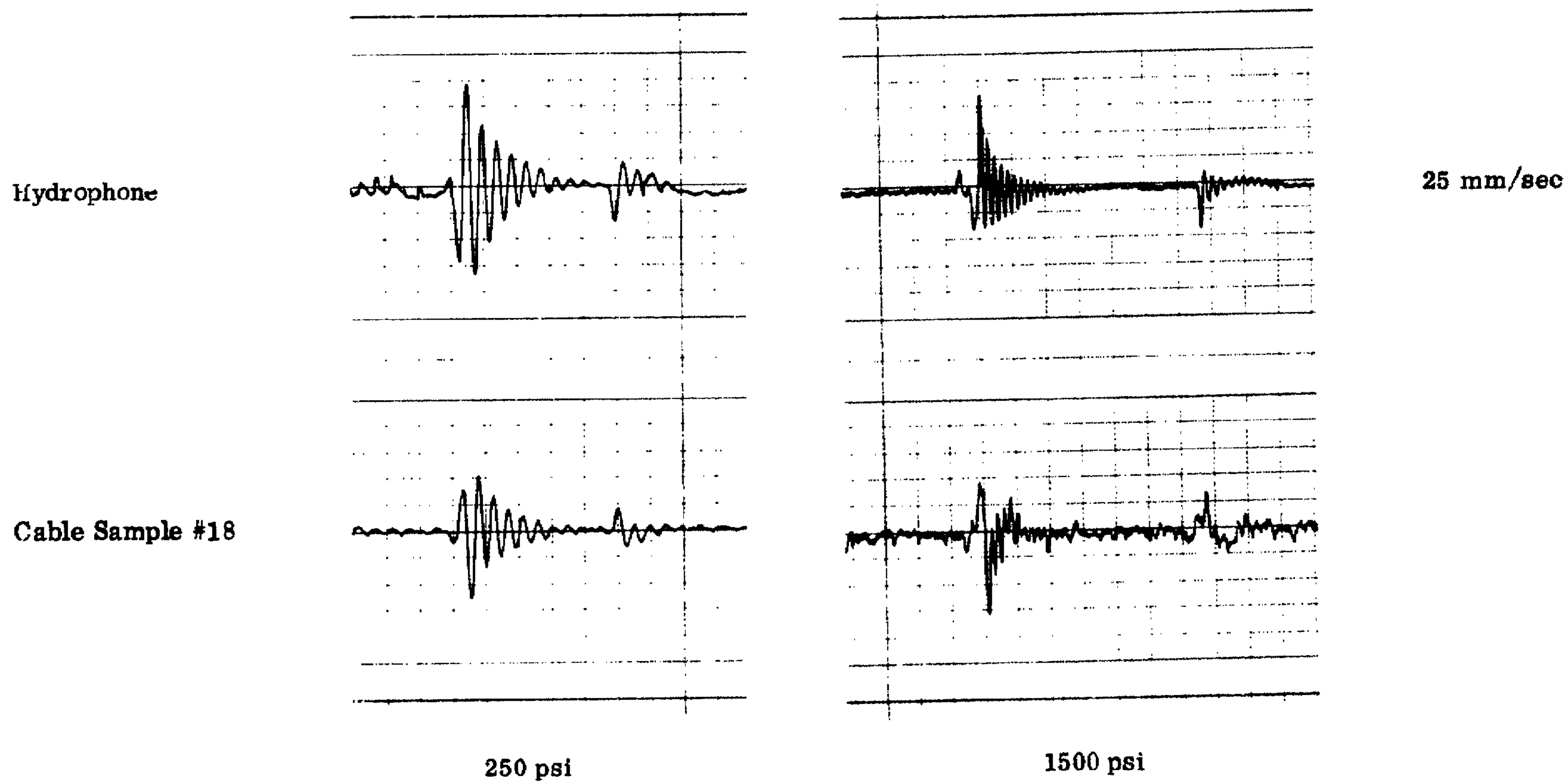


Figure 3-7. Pump-Cycle Signals at Two Pressures

3.3.2 (Continued)

has increased from 10 Hz at 250 psi to about 23 Hz at 1500 psi (a factor of 2.3). This is presumed due to the increased velocity which is expected to increase as the square root of the pressure increase. This shifts the dominant mode up by the same ratio, in this case about $(1500/250)^{1/2} = 2.45$.

Several pump-up runs were tape recorded using cable sample #18 before our time ran out on facility use. Figure 3-8 shows a direct chart record of a pump-up between 550 and 1500 psi. Note that both hydrophone and cable transducer signals gradually decrease as the pressure rises. This means that the pump signal itself decreases in amplitude as the pressure it must pump against increases. The occasional large impulsive signals in the cable channel only were observed for a wide range of circumstances during the testing, most of which involved high pressure. Their origins are still a matter of conjecture and they were ignored during data reduction. Possible explanations range from a pressure-induced stick-slip mechanical motion between shield strands and the dielectric to a large electromagnetic pulse radiated by unrelated equipment in the vicinity for which the charge amplifier was susceptible.

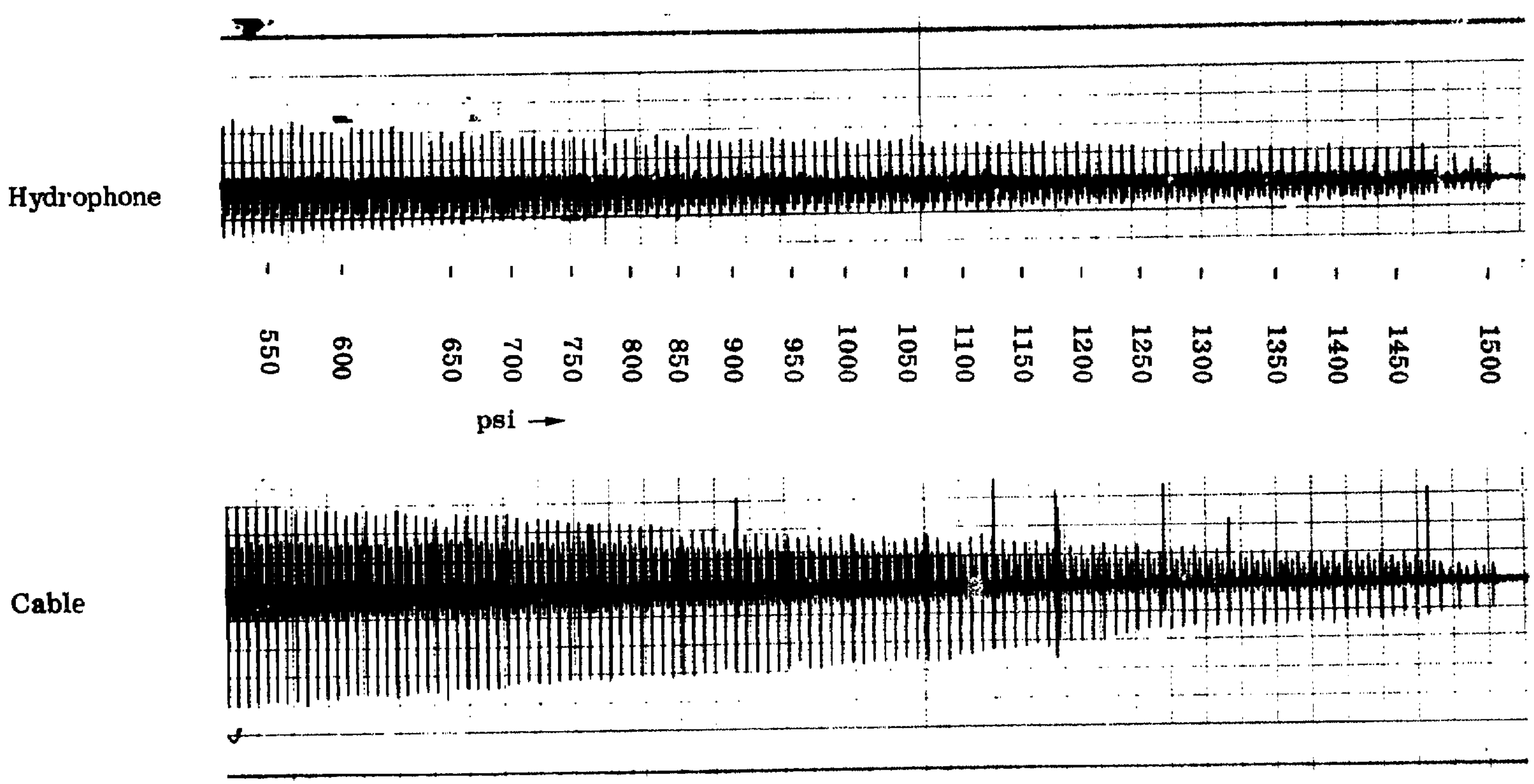


Figure 3-8. Sensor Comparison During Pressure Chamber Pump-Up

4.0 RESULTS AND DISCUSSION

The main result of this study is shown in Figure 4-1. Here the sensitivity of the cable transducer relative to that of the hydrophone is plotted as a function of ambient pressure over the range from 1 to 170 atmospheres. The circles and triangles represent data from pump-up runs on different days. The squares represent data resulting from hammer blow excitation. All data are for cable sample #18 and were recorded on tape. The plotted points are derived from the ratios of the rms values of the excitation peaks.

The main feature to be noticed is that the relative sensitivity of the cable transducer does not really change much in this pressure range. A 6 dB decrease is noted at 2500 psi relative to the sensitivity at pressures from 100 to 1000 psi. The atmospheric pressure relative sensitivity is about 10 dB below the value at mid-pressures but is somewhat in doubt. This is due to the fact that cable sample #4 in the early Lockheed tests using silicone oil showed a sensitivity at least 10 dB greater than that of the hydrophone at atmospheric pressure when excited by hammer blows on the tank. Since sample #18 is more sensitive (based on our presubmergence lab sensitivity tests) than #4, the -10.8 dB point for Figure 4-1 seems to represent a large (~20 dB) discrepancy. Unfortunately, it does not appear possible to resolve this question without further submergence tests.

A number of lessons concerning underwater transducer fabrication have been learned. It was found that if a fluid is allowed to penetrate the cable jacket, the sensitivity decreases drastically even when the fluid is a non-conductor. Waterproof potting of teflon cables is a difficult but feasible task. Imperfect seals are rapidly detected by the character of the transducer's noise, by its sensitivity drop, and in the case of a conducting fluid by the drop in DC resistance between the conductors.

Another lesson is the importance of maintaining very low contact resistances at all connections between the transducer and the charge amplifier. Several times intermittent behavior for a sample is believed to have been caused by contacts which showed dead shorts to ohmmeters but which apparently were sometimes not low enough to pass the very small signals (~ 1 pC) being generated.

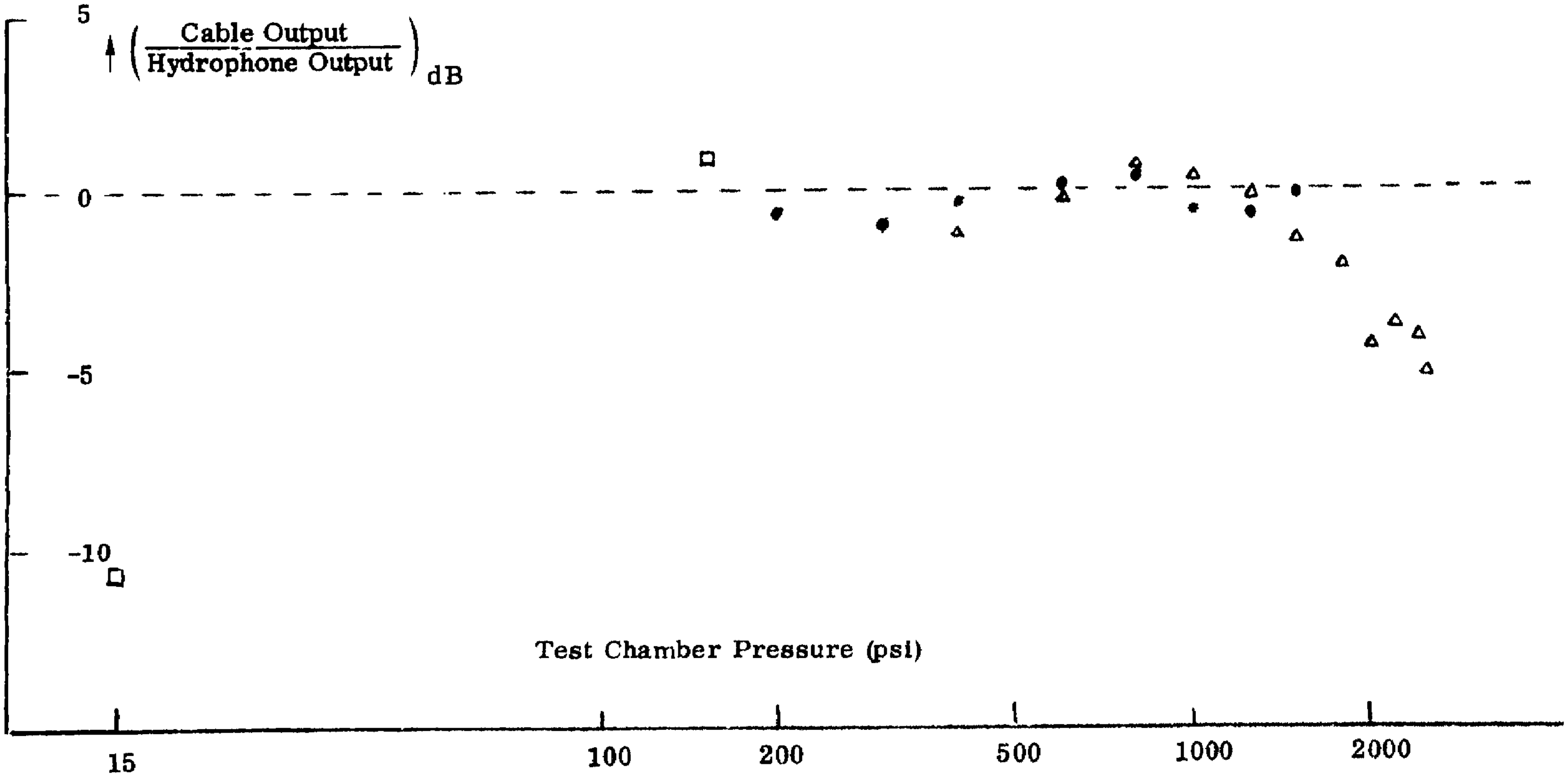


Figure 4-1. Relative Cable Transducer Sensitivity Versus Pressure

4.0 (Continued)

It would be nice to be able to point to a theoretical model to explain the variation of sensitivity with pressure shown in Figure 4-1. However, as yet only pieces of such a model have been developed. The best that can be done at this time is the following guided hand-waving exercise.

For pressures in the neighborhood of one atmosphere, the radial stiffness of the shield-jacket layers controls the motion between the shield and the dielectric and, therefore, the sensitivity. As the pressure increases the effective spacing between the shield and dielectric decreases which increases the sensitivity. (The potential increase is about 11 dB for the cable used.) However, the decrease in air gap produces a rapid increase in its stiffness so that soon it, and not the shield-jacket layer, becomes the controlling stiffness limiting the motion for a given pressure signal. This should cause the sensitivity to decrease, thus counteracting the increase caused by the closer spacing. Eventually the air gap becomes so small that its stiffness is greater than that of the teflon dielectric layer so that this becomes the motion-controlling factor. But it is noted in Figure 2-6 that the dynamic elastic modulus for FEP teflon decreases rapidly with increasing ambient pressures for pressures above about 600 psi. The corresponding decrease in the dielectric's stiffness may be sufficient to keep the sensitivity from dropping with increasing pressure up to about 1500 psi. It is felt that this heuristic explanation for the observations can be refined considerably, but that it includes the relevant qualitative factors.

5.0 CONCLUSIONS AND RECOMMENDATIONS

It has been shown that an inexpensive coaxial cable line transducer can be prepared and treated in such a way as to make an underwater transducer which is sensitive to variational pressure signals. Its sensitivity is very similar to that of a typical hydrophone and does not vary by more than about ± 6 dB when exposed to ambient fluid pressures in the range of 15 to 2500 psi.

In view of the fact that these results are based on measurements made on a single type of coaxial cable that was known to be successful in above-water applications, it is of interest to determine whether other coaxial cables or other configurations of electret transducers might provide improvements in sensitivity, immunity to changes in ambient pressure, economy, frequency response, ruggedness, or immunity to vibration. It is recommended that the next phase be aimed at consolidating the position of the present transducer with respect to these questions. Following that it would be of interest to examine other cables or configurations in these regards.

6.0 FURTHER WORK AND PLANS

6.1 INTRODUCTION

The previous sections report work completed in November 1972. Recently several additional tasks have been undertaken to further investigate the characteristics of the coaxial electret cables under various operating environments. In particular the three main objectives for this program extension are (1) determine the effects of long term high pressure on the sensor, (2) determine the sensitivity of the sensor to vibration, and (3) determine the frequency response characteristic as a function of pressure for the sensors.

6.2 IMPLEMENTATION

Figure 6-1 shows a task flow diagram for a program designed to accomplish the above goals. The blocks are numbered in the order of execution. At the present time, the first four tasks are completed or nearly completed.

The main problem encountered so far has been the difficulty of accomplishing task 2, the development of a reliable lab test which measures sample sensitivity to variational pressure signals. It was intended to design a steady-state, single controllable frequency test using tiny glass beads to simulate a fluid and transmit the signal pressure to the sample. However, so far structure-borne vibration excitation has plagued this apparatus. Preliminary results obtained using a second design based on a transient excitation signal are favorable.

The ordered materials have all been received except for the new cable. This item was not crucial since enough old cable was available for making the first set of samples. The new cable is expected in any day now, so that new sets of cable samples can be fabricated as required.

The potting technique has been refined so that reliable waterproof connectors and terminations can be applied to the samples. At atmospheric pressure no leaks have been noted for a period of several weeks of submergence.

The pressure chamber for the long term pressure test has been rented along with pressurizing gear. The fittings have been installed twice so far but a satisfactory leak-proof system has not been attained. We expect to remedy this in the near future.

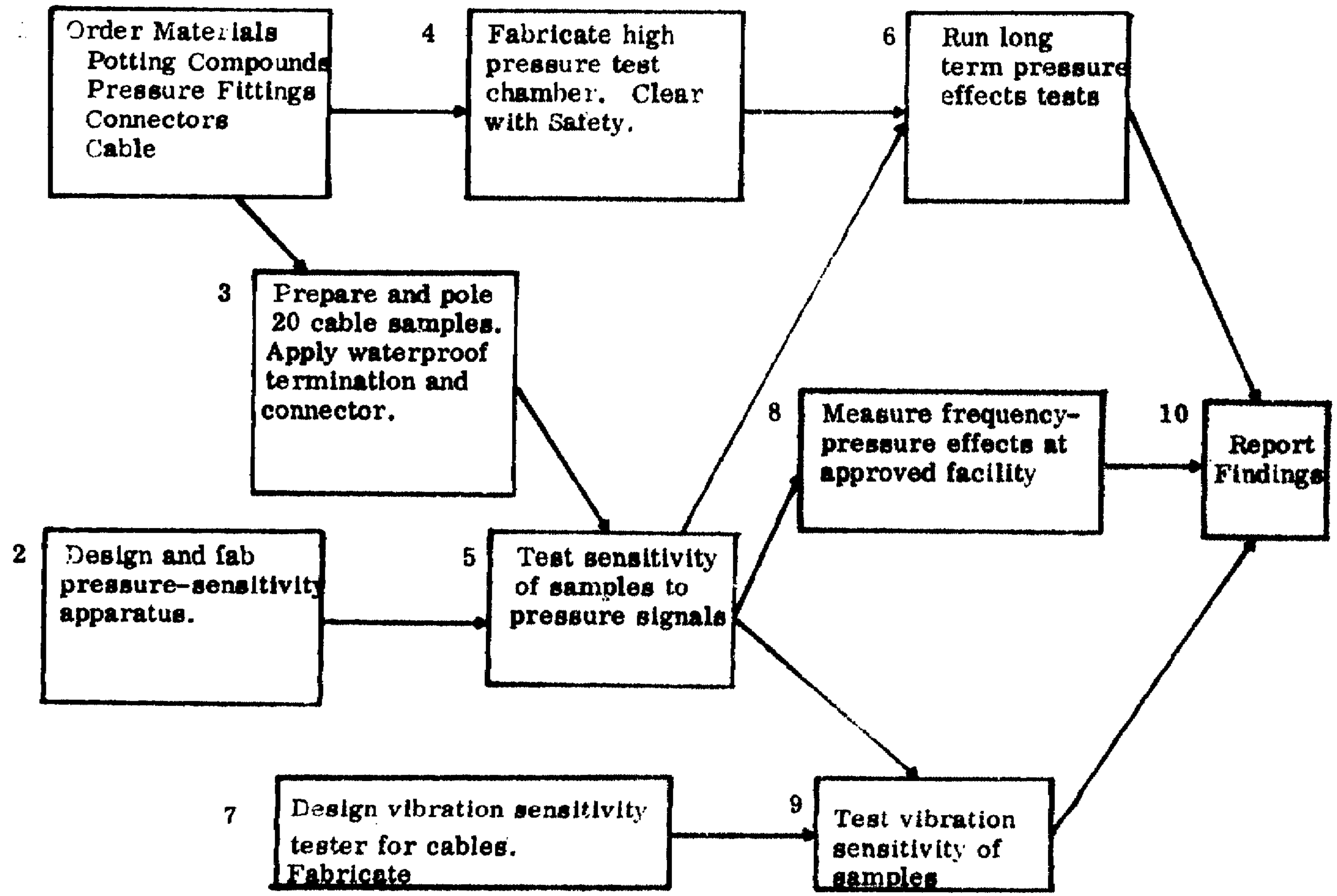


Figure 6-1. Task Performance Plan

6.2 (Continued)

Meanwhile arrangements for using the test facility run by NRL-USRD at Orlando, Florida have been made for the end of June. By preparing our samples to mate with the connectors in the facility we hope to get the maximum useful results for the time used at the facility.

The subsequent work will depend on the outcome of tasks 6, 8, and 9 of Figure 6-1. If possible, several non-cable configurations will be investigated briefly.

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13. ABSTRACT

A promising new line mechanoelectrical transducer based on the electret phenomenon is considered for use a variational pressure sensor in the under-water environment. Theoretical design considerations are developed for these coaxial cable devices with regard to sensitivity, geometry, frequency, input electronics type, and ambient pressure. Test results are reported comparing samples of one type of cable transducer to a calibrated hydrophone under two different test set-ups, for a variety of ambient pressures, and using two different types of excitation. In these tests, the cable transducer is found to compare favorably with the standard hydrophone with respect to sensitivity and independence of ambient pressure up to 2500 psi.

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